

Dynamics of Oceanic Motions

Professor Allan R. Robinson
Division of Engineering and Applied Sciences
Department of Earth and Planetary Sciences
Harvard University
29 Oxford Street
Cambridge, MA 02138-2901

Phone: (617) 495-2819, Fax: (617) 495-5192, Email: robinson@pacific.deas.harvard.edu

Award #: N000149510371
<http://www.deas.harvard.edu/~robinson>

LONG-TERM GOALS

This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: the knowledge of realistic regional processes and general physical and physical/acoustical processes; and the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

OBJECTIVES

General objectives are:

- (I) To determine for the coastal and/or coupled deep ocean the multiscale processes which occur in:
- (II)
 - i) the physical response to external and boundary forcings and via internal dynamical processes;
 - ii) the physical-biological-chemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
 - iii) the physical-acoustical interactions which influence acoustic propagation and tomographic inversions.

(II) To nowcast, forecast and simulate with data assimilation realistic oceanic fields with (sub) mesoscale resolution over large-scale domains and to understand the essential dynamics controlling forecasts and regional predictability. Specific objectives include:

- i) Northwest Atlantic shelf seas studies with atmospheric and river fluxes;
- ii) regional Mediterranean studies;
- iii) extension and application of our balance of terms scheme (EVA) to multiscale, interdisciplinary fields with data assimilation;

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Dynamics of Oceanic Motions		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Division of Engineering and Applied Sciences,,Department of Earth and Planetary Sciences,,Harvard University,29 Oxford Street,,Cambridge,,MA, 02138		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: the knowledge of realistic regional processes and general physical and physical/acoustical processes; and the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a REPORT unclassified	b ABSTRACT unclassified	c THIS PAGE unclassified			

- iv) extension and application of our hybrid ESSE data assimilation scheme to interdisciplinary fields and parameter estimation;
- v) regional predictability studies; and,
- vi) theoretical bases for objective adaptive sampling and automated verification.

APPROACH

Field estimates are obtained via the melding of data and dynamics in a modular, flexible forecast and simulation system (Harvard Ocean Prediction System - HOPS). Dynamically adjusted fields are used in physical, acoustical and biogeochemical/ecosystem process analyses based on the balance of terms of the dynamical equations. Data assimilation is carried out for dynamical adjustment, dynamical interpolation and data-driven simulations. Assimilation algorithms include a robust “optimal” interpolation scheme and a hybrid method for evolving forecast errors based on an Empirical Orthogonal Function (EOF) representation of the dominant error subspace and an ensemble forecast error estimate (Error Subspace Statistical Estimation - ESSE). The pre-treatment of data before assimilation, via structured data models (e.g. feature models), maximizes the data information content. A sequence of two-way nested model domains and nested observational strategies are used to establish accurate representations of multi-scale processes and interactions.

Energy and Vorticity Analysis (EVA) is a methodology for dynamical process diagnosis. Multi-scale EVA (MS-EVA) is a new version of EVA which is capable of multi-scale energetic studies. We approach the problem by first designing a self-similar, scale-windowed, highly localized transform, called a multi-scale window transform, and then formulating on its basis the multi-scale energetics.

WORK COMPLETED

A set of studies which describe coupled physical and biological modeling, data assimilation methodology and coupled physical and biological processes in the Gulf Stream Region have appeared [1,2]. The evolution of the temperature, salinity and circulation fields, from large scale to mesoscale, for the Black Sea in summer, were studied using HOPS [3]. Feature models for the circulation of the Gulf of Maine have been developed and documented [13,14]. The features of dominant mesoscale variability, circulation patterns and main dynamics occurring in the Strait of Sicily were studied and classified [5]. The estimation of (initial) error and variability subspaces based on ESSE is described in [4] and sensitivity studies for the Levantine sea are carried out in [15]. The transfer of environmental uncertainties to acoustic fields was carried out via ESSE for the PRIMER region [9]. The MS-EVA has been validated with a classical problem and applied to the Iceland-Faeroes Front region.

New general overviews were prepared of data assimilation [8, 17], which include short descriptions of our recent work. A report of the GLOBEC workshop on "the assimilation of biological data in coupled physical/ecosystem models" was prepared and edited [16]. A general and detailed review of data assimilation for modeling and predicting coupled physical-biological interactions in the sea was completed [9]. A new volume of THE SEA on biological-physical interactions in the sea was edited and its publication is imminent [10]. Included within that volume is an introduction that synthesizes the findings of the various authors and discusses research directions [7] as well as the review of methods of data assimilation for coupled physical-biological interactions [9]. An important overview of the circulation of the Mediterranean Sea [11] was prepared for the Encyclopedia of Ocean Sciences.

A major workshop on the "Interdisciplinary Ocean Science of the Global Coastal Ocean" in Paris, France was chaired by the Principal Investigator in August 2001 for the IOC Coastal Ocean Advanced Scientific and Technical Studies (COASTS) program. This workshop serves as the starting point for two additional volumes of THE SEA. Important concepts regarding data assimilation for modeling and predicting coupled biological/physical interactions were presented at the International Liege Colloquium on Ocean Hydrodynamics in Liege, Belgium in May 2001. Several presentations and lectures were given throughout the year by Dr. Pierre F.J. Lermusiaux as well as by the principal investigator. Additional information on the work accomplished for this project is available via the principal investigator's web site: <http://www.deas.harvard.edu/~robinson> .

RESULTS

A technique has been derived for deriving the necessary, dynamically consistent, compatible 3-D physical and biological field estimates from data for initialization and assimilation into time-evolving model simulations [1]. This technique prevents the development of spurious cross-frontal fluxes of biological quantities due to misalignment of physical and biological fronts. The application of this technique [2] to the Gulf Stream front emphasizes the importance of sub-mesoscale events between interacting mesoscale physical features in the transport of nutrients and plankton. The use of HOPS to examine the evolution of the summer circulation of the Black Sea at mesoscale resolution re-affirmed the shape and propagation parameters of the Rim Current, eddy size and distribution and the generation of rapid surface-bound jets [3]. In addition, the simulation shows previously unobserved events for which evidence can be found in historic observations.

Feature-oriented regional modeling for various types of front are presented in a generalized approach in [14]. Large-scale meandering frontal systems such as the Gulf Stream, Kuroshio, etc. can be modeled via velocity-based feature models. Buoyancy forced coastal water mass fronts such as coastal currents, tidal fronts, inflow/outflow fronts, etc. can be modeled by a generalized parameterized water mass feature model. The multi-scale synoptic circulation systems in the Gulf of Maine and Georges Bank region are summarized using a feature-oriented approach in [13]. A synoptic initialization scheme for feature-oriented regional modeling and simulation of the buoyancy-driven circulation in the coastal-to-deep region has been developed. The applicability of feature-oriented regional modeling and simulation for multi-scale, multi-domain, multi-platform and multi-disciplinary nested forecast systems has been demonstrated.

Combining hydrographic data with HOPS by data assimilation, the main features of dominant mesoscale to sub-basin-scale variability in the Strait of Sicily during the summer of 1996 have been estimated and revealed, and several of their dynamical properties described [5]. The dominant dynamical variations were revealed to be linked to the Atlantic Ionian Stream and associated with five features: the Adventure Bank Vortex, Maltese Channel Crest, Ionian Shelfbreak Vortex, Messina Rise Vortex, and temperature and salinity fronts of the Ionian slope.

The use of error subspace allows for an accurate, global, multi-scale and multi-variate, three-dimensional analysis of primitive equation fields and their errors in real time [4], as demonstrated for the Middle Atlantic Bight and the eastern Mediterranean. The modern methodology of relating natural data and dynamical models to provide estimates of nature which are better estimates than can be achieved by using only the observational data or the dynamical model has been described in [8]. This document introduces concepts, describes purposes, presents applications to regional dynamics and

forecasting, overviews formalisms and methods and provides a range of examples. The extension to highly non-linear coupled biological-physical dynamics is documented in [9] through a series of case studies.

The uncertainties in the predicted acoustic wavefield associated with the transmission of low-frequency sound from the continental slope, through the shelfbreak front, onto the continental shelf have been examined in [6]. The combined ocean and acoustic results from the simulation study provides insights into the relations between the uncertainties in the ocean and acoustic estimates.

The Assessment of Skill for Coastal Ocean Transients (ASCOT) experiment of June 2001 (ASCOT-01) has resulted in a unique set of compatible physical, biological, and chemical multiscale observations. This data set forms the basis for ongoing interactive process studies and interdisciplinary data assimilation, adaptive sampling, and predictive skill OSSEs for Massachusetts Bay and the Gulf of Maine. Research is in progress on: the estimation and identification of forecast skill and error and the development of automated skill metrics; processes and dynamics of the region and their effect on accurate forecasting; and, regional interdisciplinary processes.

The Generic Oceanographic Array Technology System/Multi-Scale Environmental Assessment Network Studies (GOATS/MEANS 2000) exercise of September-October 2000 identified a unique dynamical event, the generation of an anti-cyclone, in the nested modeling domains [12]. The dynamics of the generation of this anti-cyclone, which had not previously been named or identified, are under investigation. In addition, the regional dynamics and response to wind events continue to be of interest.

A general analytical theoretical approach to the study of advective effects on biological oceanographic dynamics has been formulated, developed and applied to the study of some idealized processes of real ocean interest. This approach complements related process research based upon experimentation and numerical simulation. Figure 1 exemplifies the application of this theoretical approach. New results include: a detailed study of zooplankton mortality in the context of the general solution; the addition of a mixed layer on top of the euphotic zone which can significantly alter previous results both qualitatively and quantitatively; and, the essential completion of a theoretical formula for coastal upwelling and mesoscale eddy vertical advection. Publications documenting these results are currently in preparation.

IMPACT/APPLICATIONS

The important ESSE concept is that the evolution of 3D multivariate forecast variability and error can be efficiently described by a small number of adequate functions (e.g. error EOFs). The most energetic variability and error fields are expected to evolve in limited subspaces. In general, ESSE is useful for a wide range of applications, including nonlinear field and error forecasting, finding numerical instabilities, performing predictability studies, objective analyses, data-driven simulations, adaptive sampling and parameter estimation.

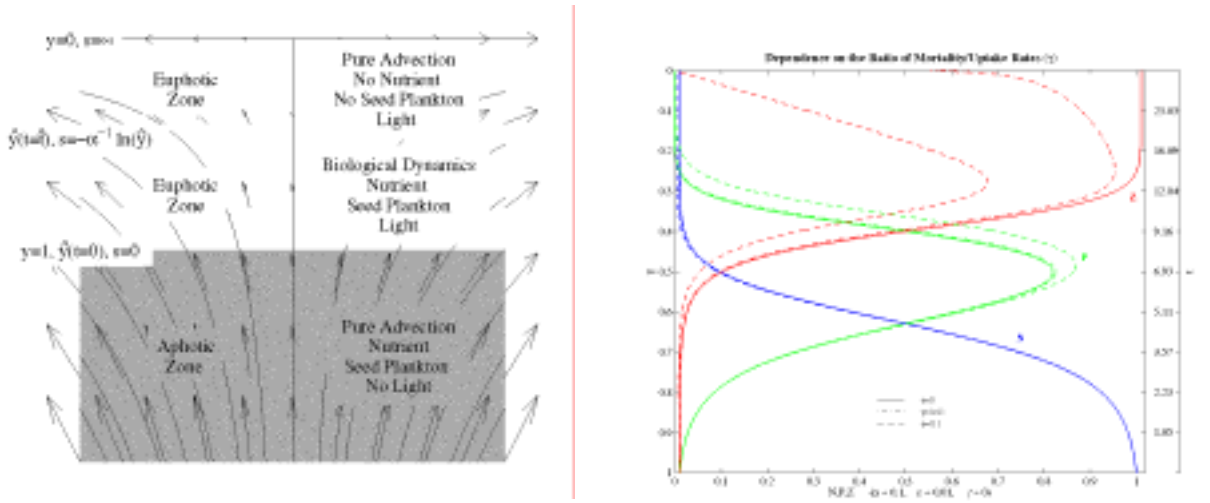


Figure 1. (left) example application of analytic theory applied in a steady upwelling situation; (right) result of analytic theory showing parameter dependencies of upwelling processes on N (Blue), P (Green), Z (Red) system. Conversion of Nutrients to Phytoplankton and the grazing by Zooplankton is indicated.

Analytic theory and numerical simulations have improved our understanding of the biological response to physical processes in fronts and mesoscale patches. This improved understanding will prove useful to the basic research and applied research scientific communities. The role of coupled biological/physical data assimilation and application of existing methods is an important focus of our research. Since data assimilation intimately links dynamical models and observations, it can play a critical role in the important area of fundamental biological oceanographic dynamical model development and validation over a hierarchy of complexities. The emergence of realistic interdisciplinary four-dimensional data assimilative ocean models and systems is contributing significantly and increasingly to this progress. It is anticipated that Volume 12 of THE SEA will have a significant impact on research directions in a broad sense.

Real-time regional forecasting research results are directly applicable to the design of ocean prediction and monitoring systems for: naval operations; research operations; the efficient environmental management of, and commercial operations within, a multi-use Exclusive Economic Zone; interdisciplinary global change research.

TRANSITIONS

Definitive results are passed to the Harvard 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)" with the same principal investigator. The ESSE methodologies and codes continue to be transferred to ROMS-TOMS in collaboration with Rutgers University. Work continues with UMass-Dartmouth in the transition of HOPS to a Regional Fisheries Applications Center (RFAC).

RELATED PROJECTS

This project is closely related to other Harvard projects, including: a new NSF-OIT project "Rapid Real Time Interdisciplinary Ocean Forecasting Adaptive Sampling and Adaptive Modeling in a Distributed Environment" (Prof. N. Patrikalakis and Prof. H. Schmidt - MIT; Prof. J.J. McCarthy - Harvard); the new ONR project "Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture", and other Harvard research. In addition, important collaborations are ongoing with NRL Stennis (Dr. A. Warn-Varnas); U. Colorado (Dr. L. Kantha); IMGA, Modena, Italy (Dr. N. Pinardi); and the Naval Postgraduate School (Dr. Ching-Sang Chiu).

PUBLICATIONS

- [1] Anderson, L.A., A.R. Robinson and C.J. Lozano, 2000. Physical and Biological Modeling in the Gulf Stream Region: I. Data Assimilation Methodology. *Deep-Sea Research I*, 47, 1787-1827.
- [2] Anderson, L.A. and A.R. Robinson, 2001. Physical and Biological Modeling in the Gulf Stream Region, II: Physical and Biological Processes. *Deep-Sea Research I*, 48, 1139-1168.
- [3] Besiktepe, S., C.J. Lozano and A.R. Robinson, 2001. On the Summer Mesoscale Variability of the Black Sea. *Journal of Marine Research*, 59, 475-515.
- [4] Lermusiaux, P.F.J., D.G. Anderson and C.J. Lozano, 2000. On the Mapping of Multivariate Geophysical Fields: Error and Variability Subspace Estimates. *Q.J.R. Meteorol. Soc.*, April B, 1387-1430.
- [5] Lermusiaux, P.F.J. and A.R. Robinson, 2001. Features of Dominant Mesoscale Variability, Circulation Patterns and Dynamics in the Strait of Sicily. *Deep-Sea Research I*, 48, 1953-1997.

PUBLICATIONS (IN PRESS AND SUBMITTED)

- [6] Lermusiaux P.F.J., C.-S. Chiu and A.R. Robinson, 2001. Modeling Uncertainties in the Prediction of the Acoustic Wavefield in a Shelfbreak Environment. *Proceedings of the 5th International conference on theoretical and computational acoustics*, May 21-25, 2001. Beijing, China. In press.
- [7] McCarthy, J.J., A.R. Robinson and B.J. Rothschild, 2001. Chapter 1 - Biological-Physical Interactions in the Sea: Emergent Findings and New Directions. *THE SEA: Volume 12: Biological-Physical Interactions in the Sea*, Robinson, A.R., J.J. McCarthy, and B.J. Rothschild (editors), in press.
- [8] Robinson, A.R. and P.F.J. Lermusiaux, 2001. Models: Data Assimilation (Physical/Interdisciplinary). *Encyclopedia of Ocean Sciences*. Academic Press Ltd., London, in press.
- [9] Robinson, A.R. and P.F.J. Lermusiaux, 2001. Data Assimilation for Modeling and Predicting Coupled Physical-Biological Interactions in the Sea. *THE SEA: Volume 12: Biological-Physical Interactions in the Sea*. Robinson, A.R., J.J. McCarthy and B.J. Rothschild (editors), in press.

- [10] Robinson, A.R., J.J. McCarthy and B.J. Rothschild (editors), 2001, *THE SEA: Volume 12: Biological-Physical Interactions in the Sea*, in press.
- [11] Robinson, A.R., A. Theocharis, A. Lascaratos and W.G. Leslie, 2001. Ocean Currents: Mediterranean Sea Circulation. *Encyclopedia of Ocean Sciences*. Academic Press Ltd., London, in press.
- [12] Robinson A.R., J. Sellschopp, W.G. Leslie, A. Alvarez, G. Baldasserini, P.J. Haley, P.F.J. Lermusiaux, C.J. Lozano, E. Nacini, R. Onken, R. Stoner, P. Zanasca, 2001. Forecasting synoptic transients in the Eastern Ligurian Sea. In *Rapid Environmental Assessment*, Saclantcen conference proceedings series, Saclantcen, La Spezia, Italy. In press.
- [13] Gangopadhyay, A., A.R. Robinson, P.J. Haley, Jr., W.G. Leslie, C.J. Lozano and J.J. Bisagni, 2000. Feature Oriented Regional Modeling and Simulations (FORMS) In the Gulf of Maine and Georges Bank. *Continental Shelf Research*, submitted.
- [14] Robinson, A.R. and A. Gangopadhyay, 2001. Feature Oriented Regional Modeling of Oceanic Fronts. *Dynamics of Atmospheres and Oceans*, submitted.

NON-REFEREED PUBLICATIONS

- [15] Lermusiaux P.F.J., C.J. Lozano and D.G.M. Anderson, 2001. On the mapping of multivariate geophysical fields: studies of the sensitivity to error subspace parameters. Harvard Reports in Physical/Interdisciplinary Ocean Science. No. 60.
- [16] Robinson A.R. and P.F.J. Lermusiaux (Eds.), 2000. Workshop on the assimilation of biological data in coupled physical/ecosystem models. CNR Research Area, Bologna, Italy, June 28-30, 1999. GLOBEC Special Contribution 3, 152pp.
- [17] Robinson A.R. and P.F.J. Lermusiaux, 2000. Overview of data assimilation. Harvard Reports in Physical/Interdisciplinary Ocean Science. No. 62.